Documentation of the performance gap

Jensen, Søren Østergaard; Wittchen, Kim B.; Rose, Jørgen

DANISH TECHNOLOGICAL INSTITUTE

DANISH BUILDING RESEARCH INSTITUTE
AALBORG UNIVERSITY COPENHAGEN

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Søren Østergaard Jensen, Danish Technological Institute
Kim Wittchen and Jørgen Rose, Danish Buildings Research Institute

Introduction

It is the general experience that energy efficient new or renovated buildings perform differently than expected with regard to energy consumption. The buildings often have higher energy consumption than expected.

The reasons for the difference between the calculated energy demand during the design phase and the realized usage are typically:

- errors in the input to the design tool or the design tool cannot handle specific features of the building correctly,
- changes in the design of the building and/or constructions as well as energy service systems during the building process,
- other demands and usages than the standard conditions used in the applied design tool,
- different climatic conditions compared to the weather data used in the design tool,
- faults, inadequate balancing and commissioning of the building constructions and the energy service systems of the building.

The performance of energy efficient buildings is furthermore more sensitive to differences between the assumed and the actual design than earlier, less energy efficient buildings. Therefore, it is not possible simply to compare the calculated annual energy demand from the design phase with the measured annual energy usage when evaluating if a building fulfils the requirements specified during the design phase.

Based on the above bullet points (Jensen, 2013) describes a method on how to evaluate if a building performs as expected. This method has been utilized in the following.

Two examples of documenting the performance gap

The two examples dealt with in the following are Sems Have consisting of two buildings that went through an extensive renovation and BOLIG+, which is the first Danish energy neutral apartment block. The aim of the two projects was that their final energy demand should comply with the Danish Building Class 2020 (Danish Building Regulation 2010) with an annual primary energy demand of no more than 20 kWh/m^2. BOLIG+ should further be energy neutral in the sense that the same amount of primary energy and its usability should be produced at the building as is used in the building including both energy for operating the building and the energy use of the occupants in the apartments.

For the two buildings the energy demand calculated during the design phase is compared to the actual measured energy usage. The energy demand calculated during the design phase was calculated with Be10 (Aggerholm and Grau, 2014), which was used to determine if a building complied with the allowed energy demand stated by the Danish Building Regulation 2010. The calculation is based on standard values in order to be able to compare the energy performance with the requirements of the calculation standard and with other buildings. Some of these standard values are: an indoor temperature of 20°C, an annual domestic hot water (DHW) demand of 250 l/m^2, heat gains from people and appliances of 5 W/m^2, a ventilation flow rate of 0.3 l/s/m^2 and an infiltration rate of less than 0.07 l/s/m^2 (the latter is only for Building Class 2020 buildings, other buildings are assumed to have an infiltration rate of less than 0.1 l/s/m^2).

The applied primary energy factors in the following calculations were district heating: 0.6 (both buildings were heated by district heating) and electricity: 1.8 as specified for Building Class 2020.

Sems Have

Sems Have was originally constructed in 1970-72 under the name “House of youth”. The two buildings were a four-story building with a dormitory at the first to fourth floor, and an activity centre for school-children at the ground floor. The other building contained a day-care centre for small children at the ground floor and two smaller concert halls at the first floor. In 2011 the buildings were totally worn down and the housing association had to decide if the buildings should be demolished or refurbished. Based on economical calculations it was decided to refurbish the buildings and turn them into 30 modern low energy apartments. Figure 1 shows the buildings before and after the renovation.

Figure 1. Sems Have/House of youth before (left) and after (right) the renovation. Not only the interior but also the exterior went through a major renovation.

In the following, mainly the heating demand is considered.

The annual heating demand (space heating and DWH including heat losses from the energy service systems) was during the design phase calculated to 25.5 kWh/m², but the measurements show and annual heating consumption of 53.8 kWh/m² – or more than twice the calculated heat demand.

This could indicate that the buildings are performing poorly, or are they? In order to determine this it is necessary to calibrate the calculation model to the actual conditions. It was warmer during the investigated year than in the weather file used in the calculation program. There were 28 % less heating degree-days than in the standard weather file. To account for this, the measured space heating demand was increased by 28 % leading to an overall heating demand of 63.2 kWh/m² in order to be able to compare with the initial calculations. However, this actually makes the buildings seem even worse performing.

Based on measurements in some apartments it was determined that the room temperature was higher than 20°C, most likely with a mean value of 23°C. The air change was determined to be 0.48 l/s/m², and as the buildings were not exposed to a pressure test, the infiltration is, therefore, more likely 0.1 rather than 0.07 l/s/m² as it should be according to the Building Class 2020 requirements. This leads to an airflow of 0.41 l/s/m² via the ventilation systems and not 0.3 l/s/m² as assumed in the initial calculations. The heat gains in the actual building were, based on the actual number of persons living in the building and the normal number of appliances, calculated to be 4.8 and thus close to the standard value of 5 W/m². The DHW demand was measured and found to be close to 250 l/m² (the standard value). When introducing these changes in the building model the annual space heating demand was increased to 41.9 kWh/m², which is much closer to the measured and climate corrected heating demand of 63.2 kWh/m².

After this, the energy service systems were evaluated. The main observed discrepancies, when comparing to the input parameters of the calculation tool, were: missing heat losses in the ventilation systems in the attics including losses from piping and ducting, and not all hot (DHW and space heating) pipes in the cellars were accounted for. When accounting the for additional heat losses from the ventilation systems including ducting, the calculated heat demand increases to 45.8 kWh/m². In order to reach the measured and weather corrected heat demand of 63.2 kWh/m² there is a need for including the heat loss from 1,150 m piping for both space heating and DHW in the cellar, which is actually not unrealistic, considering the length of the buildings, many parallel pipes, and that the two buildings are connected by a 13 m cellar where piping is also located. This extra amount of piping may also cover heat losses not found during the inspections of the buildings.

Based on the above it can be stated that approx. half of the higher heat consumption compared to the originally calculated demand is due to different use of the buildings, while the other half is due to not included heat losses from the ventilation system incl. ducting and piping in the original calculations.

The above calibrated Be10 model was then used to calculated the energy demand with the standard values for room temperature, free gains and DHW – i.e. normalized to the use of the buildings. This leads to an annual heat demand of 44.7 kWh/m².

The electricity demand for operating the building was assumed to be 6.1 kWh/m² but measured to 6.6 kWh/m², while the production from the two PV system was assumed to be 3.8 kWh/m² but was measured to be 5.2 kWh/m². However, there was slightly more solar radiation compared to the standard year, so the PV production has to be reduced to 4.7 kW/m².

Based on the above the primary energy demand with standard values can be calculated to 44.7*0.6+(6.6-4.7)*1.8 = 30.2 kWh/m², which is 51 % more than the 20 kWh/m², that was aimed for. The excess energy consumption is, however, far less than at first sight when directly comparting the calculated and measured heat consumption of the buildings, the latter was more than twice as high as anticipated during the design of the building. The calibration exercise was, thus, necessary in order to be able to judge how well the buildings perform.

More information on Sems Have and the performed energy calculations may be found in (Jensen et al. 2017) and (Rose et al., 2018).

BOLIG+

The BOLIG+ was the result of a more than 10 years process in developing energy neutral residential buildings. The history of the BOLIG+ process are found on boligplus.org.

BOLIG+ is a new building with 10 low energy apartments. In addition to being energy-neutral, the building should comply with the Building Class 2020 without any subtraction of electricity produced at the building. Figure 2 shows BOLIG+. The black areas on the facades are different angled PV panels. The roof is also covered with PV panels.

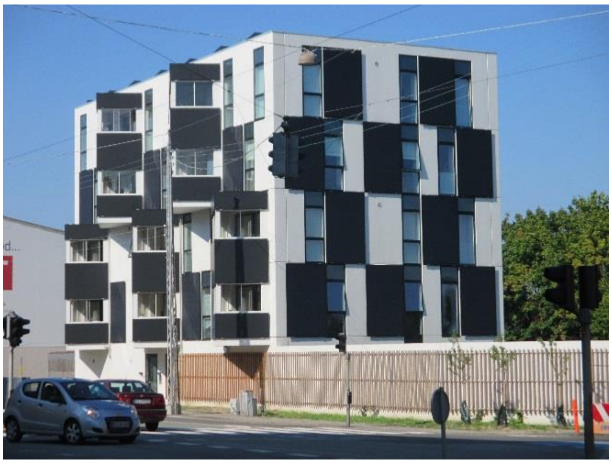

Figure 2. BOLIG+ seen from the street.

In the following, mainly the heating demand of the buildings is evaluated.

The design tool (Be10) estimated an annual heating demand of 43.5 MWh while the real annual heating usage was measured to 47.3 MWh. This is only a 9 % higher heating demand than anticipated during the design. So, within the uncertainty of the calculation and the measurements the building performs as it should – or does it? This is investigated in the following.

Table 1 shows some of the input parameters to Be10 during the design phase (left column) compared to the same parameters measured in the actual building (right).

Table 1. Input parameters to Be10 during the design phase compared with the actual measured values. [1)] the volume of the DHW is decrease because of heat recovery on the water from the bathrooms.

	Design	Measured
Room temperature	20 °C	22.8 °C
Heat gains from persons	1.5 W/m²	1.03 W/m²
Heat gains from appliances	3.5 W/m²	2.4 W/m²
Mechanical ventilation	0.32 l/s/m²	0.347 l/s/m²
Infiltration	0.07 l/s/m²	0.064 l/s/m²
DHW	175 l/m² [1)]	162 l/m² [1)]
Temperature of DHW	55°C	54°C

Table 1 shows that the indoor temperature was higher than foreseen, while the heat gains were lower. The mechanical ventilation airflow rate was a bit higher, while the infiltration rate was a bit lower. Both DHW consumption and the temperature of the DHW was a bit lower in the actual building.

Furthermore, the total solar radiation was almost the same as in the weather file in Be10, while the ambient temperature most of the time was higher. The number of heating degree-days in the actual year was 3033, while in the weather file in Be10 it is 3200.

When introducing the measured values from table 1 and a milder climate in Be10 the calculated heating demand changes from 43.5 MWh to 36.8 MWh, which is much lower than the measured: 47.3 MWh.

When investigating the measurements it is observed, that the actual buildings has a heat consumption for floor heating in the bathrooms during the summer, which normally isn't considered in a Be10 calculation for determination if a building comply with the Danish Building Regulation. It was further observed, that the length of the pipes were large and that the heat exchangers of the ventilation systems was slightly less efficient in the real building compared to the original Be10 model. When including the summer floor heating and the heat losses from the extra piping/a bit less efficient heat exchangers the calculated heating demand increased to 43.8 MWh. As the model now only calculates a 7 % too low heating demand, it was judged that it was not necessary to adjust the model further.

Some of the input values are now set to the standard values: room temperature to 20°C, heat gains to 1.5 and 3.5 W/m² (see table 1) and a higher DHW demand of 250 l/m² (minus the effect of heat recovery on the grey wastewater from the bath rooms) and without floor heating in the bathrooms during the summer. This leads to an annual heat demand of 29 kWh/m² while the heat demand in the design case was 28 kWh/m². So, overall the building performs as expected with regard to heating demand although the demand was distributed differently when compared to the original calculation. The calibration of the model hereby led to an insight, which otherwise would not have been possible.

The electricity use for operating the building was a bit higher in the real building compared to the design calculation: 2.1 vs. 1.8 kWh/m². The combination of the heating demand of 29 kWh/m² and an electricity demand of 2.1 kWh/m² leads to a primary energy demand of 29*0.6+2.1*1.8 = 21.2 kWh/m², which is only 6 % higher that the aim of 20 kWh/m². So, within the uncertainties, the building did perform as expected.

Was the building energy neutral with all the PV panels on the facades and roof? Well, the PV panels produce 26 % less than expected and the occupants used a bit more electricity in the apartments, so the building was not energy neutral. However, if the PV panels had produces as designed, and the electricity use in the apartments was as defined in the design phase, the building would only be 11 % from being energy neutral, which is actually a very good result.

More information on BOLIG+ and the performed energy calculations can be found in (Jensen, Wittchen and Knudsen, 2018) and (Wittchen, Jensen and Knudsen, 2019).

Conclusion

The calibration exercises on Sems Have and BOLIG+ show that it is not recommendable to judge the performance of a building by simply comparing the designed energy demand with the actual measured energy consumption.

For Sems Have this comparison would have led to the conclusion that the buildings performed much worse than they actually do. Half of the extra energy demand was due to different use of the buildings, while the other half was due to some heat losses not included in the original model of the buildings.

For BOLIG+ the direct comparison of the designed energy demand and the actual energy consumption led to the same overall conclusion as the calibration exercise, i.e. that the building performs as expected. However, the calibration exercise gave an insight to the actual energy flows in the building, which otherwise would have remained hidden. The actual use of the building and a milder climate lead to a lower energy demand, which was counterbalanced by not originally considered floor heating in the bathrooms during the summer and more heat losses from piping and slightly less efficient heat exchangers in the ventilation systems than in the original model of the building.

Calibration of a model of a building based on measurements it thus an important method to gain more knowledge of the actual energy performance of buildings.

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